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13. ABSTRACT *(Maximum 200 words)*

DURIP funds were used to purchase a state-of-the-art cryopumping system and a laser-induced-fluorescence (LIF) system utilizing two lasers (a 20 W UV-capable, argon-ion pump laser used in conjunction with a ring-dye laser) to enhance the vacuum and diagnostics capabilities at the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory (PEPL). Prior to the upgrade, the 9 x 6 meter diffusion-pumped vacuum chamber at PEPL had a xenon pumping speed of 27,000 l/s and could maintain a pressure of 5x 10 Torr during the operation of a 1.35 kW Hall thruster. The base pressure of the facility was approximately 2x 10 Torr. The four large nude cryopumps, used in place of the diffusion pumps, and significant leak repair work allows for a 140,000 l/s xenon pumping speed, a base pressure of 2xl0 Torr, and a clean, oil-free test environment. The facility upgrade, and the addition of LW capability, has made PEPL one of the few world-class electric propulsion test facilities in the nation.

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Establishment of a World-Class Facility for High-Power Electric Propulsion Research

F49620-97-1-0107

Final Report

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Summary

DURIP funds were used to purchase a state-of-the-art cryopumping system and two lasers for a laser-induced-fluorescence (LIF) system to enhance the then already impressive vacuum facility at the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory (PEPL). Prior to the upgrade, the 9 by 6 meter diffusion-pumped vacuum chamber at PEPL had a xenon pumping speed of 27,000 l/s and could maintain a pressure of less than 50 microtorr during the operation of an SPT-100 Hall thruster. The base pressure of the facility was approximately 20 microtorr. Our goal in soliciting funds from the DURIP program was to increase the xenon pumping speed of the PEPL chamber to 200,000 l/s, to allow high-power (5 kW) Hall thrusters to be operated at sufficiently low back pressures to permit high-fidelity spacecraft integration and thruster development programs to take place, and to apply non-intrusive laser diagnostic techniques (e.g., LIF) to study Hall thrusters and arcjets of all power levels. These acquisitions would turn the PEPL facility into one of the premier electric propulsion research centers in the world, one that can serve as a national resource to the Air Force and the electric propulsion community in general. Though we fell short of our xenon pumping speed goal (we are at 140,000 l/s) because the proposed technology had not reached the level of maturity needed, the facility upgrade nevertheless makes our chamber one of the few world-class electric propulsion test facilities in the nation.

Background Information

Propulsion systems having high exhaust velocities (Ve>10 km/s) are desirable for a variety of space missions. In order for a propulsive system not to require an inordinate amount of propellant, its exhaust velocity should be of the same order as the characteristic velocity increment (Delta-V) required for a given space mission. Studies have shown that for orbit transfer missions of interest by NASA and the DOD, a characteristic velocity increment of over six kilometers per second may be necessary [1]. Furthermore, experience gleaned from operation Desert Storm shows the need for military space assets to be rapidly repositioned without excessive use of onboard propellant; i.e., the need for high specific impulse propulsion systems of moderate thrust.

Cryogenically fueled chemical rockets which rely on the intrinsic energy available from the chemical reactions of their constituent propellants are inherently limited to exhaust velocities of 5 km/s. Chemical rockets which use "space storable" fuels such as hydrazine are limited to exhaust velocities of 3 km/s [2]. Thus, propulsion systems which produce exhaust velocities considerably higher than those obtained with chemical systems would benefit a variety of orbital space missions.

Ideally, an engine which would be used as the primary source of propulsion for satellite station-keeping and orbit repositioning in modern spacecraft should produce an exhaust velocity between 10 and 25 km/s [3]. To achieve this performance, a propulsion system must accelerate its propellant gas without relying on energy addition through chemical reactions. One approach is the application of electrical energy to a gas stream in the form of electrical heating and/or electric and magnetic body forces. This type of propulsion system is commonly known as electric propulsion (EP).

EP can be categorized into three groups [4]: i) *Electrothermal Propulsion Systems* in which a gas is electrically heated, either with resistive elements or through the use of an electric arc, and is subsequently expanding through a supersonic nozzle to produce thrust; ii) *Electromagnetic Propulsion Systems* which use electromagnetic body forces to accelerate a highly ionized plasma; and iii) *Electrostatic Propulsion Systems* which use electrostatic forces to accelerate ions.

In addition to possessing suitable exhaust velocity, an EP system must also be able to convert onboard spacecraft power into directed kinetic power of the exhaust stream efficiently (i.e., possess high thrust efficiency) and must generate suitable thrust to ensure reasonably short deployment times.

Electrothermal systems have limited utility for this role because of performance constraints placed on them by excessive frozen flow and electrode losses [5-7]. The specific impulse and thrust efficiency of arcjets operating on space-storable propellant is limited to less than 650 seconds and 41%, respectively. Steady-state electromagnetic systems have demonstrated high thrust efficiencies only at power levels that far exceed those generated onboard current spacecraft [8,9]. However, researchers at NASA Lewis Research Center (LeRC) and the University of Michigan (UM) have recently developed and evaluated a pulsed magnetoplasmadynamic (MPD) thruster which could be used for propelling orbit transfer vehicles or communication satellites with large solar power supplies (e.g., 10 kW) with moderate success [8]. Gridded electrostatic engines (e.g., ion engines), which can achieve large exhaust velocities (Ve>50 km/s) at high thrust efficiencies (>0.7), have traditionally demonstrated efficient performance at exhaust velocities above 30 km/s [4,10,11], beyond the desired range for orbit transfer missions. The high specific impulse of the ion thruster means that for a given spacecraft power level, it will generate less thrust than a lower Isp counterpart, resulting possibly in larger trip times and a demand for longer thruster life. Furthermore, ion engines pay a penalty for its high power processing specific mass due to its large operating voltages (e.g., 2000 V) and are limited in thrust density by space-charge effects, making ion thrusters considerably bulkier than other EP systems [4].

Therefore, the ideal propulsion system for orbit transfer missions and for satellite station-keeping is a compact engine of high thruster density that efficiently accelerates propellant (e.g., through electrostatic

means) to modest exhaust velocities while requiring discharge voltages of less than 1000 V. As is shown below, the Hall thruster is a device which fulfills these requirements.

The Hall Thruster

The Hall thruster is an electrostatic engine that was developed in the 1960's to alleviate the thrust density limitation of ions engines that results from space-charge effects within the acceleration volume. Hall thrusters were also attractive from the standpoint that since grids are not required to accelerate ions, they do not suffer from the large grid erosion rates of the ion engines. Interest in the Hall thruster waned in the early 1970's, however, because of budgetary cuts and because American researchers were never able to demonstrate that these engines could operate at thrust efficiencies near those achieved with ion thrusters [12-14]. As such, Hall thruster research essentially disappeared in the U.S. between 1972 and 1985. From 1985 to 1990, Ford Aerospace (now Space Systems/Loral), in conjunction with NASA LeRC, funded a small research effort to determine if Hall thrusters could be used for North-South satellite station-keeping [15]. This program proved to be unsuccessful and was abandoned.

Throughout this period, however, Hall thruster research flourished in the Soviet Union, ironically because Soviet engineers were never able to develop adequate grids for ion thrusters. Hall thrusters were first tested in space in 1971 with immediate success [16,17]. Since then, over fifty Hall thrusters have been used on Soviet and Russian spacecraft, mostly as plasma contactors and for East-West station-keeping. However, in 1994 the first satellite to use Hall thrusters for North-South Stationkeeping (NSSK) was launched by Russia. Because of this and recent experiments which show that Russian Hall thrusters are capable of generating specific impulses of 1650 seconds at thrust efficiencies of 50% [18,19], there has been a great deal of interest in using these on American spacecraft for NSSK and for orbit repositioning. For example, the Ballistic Missile Defense Organization (BMDO) is developing a flight experiment that uses a Russian Hall thruster on the U.S. Wake Shield Experiment Craft. Space System/Loral (SSL) has announced that its next generation of communication satellites will use Hall thrusters for NSSK. Clearly this device, with performance far superior to that of arcjets, which is the most advanced propulsion system currently in use on American spacecraft, would not only serve as an excellent thruster for orbit station-keeping and repositioning roles, but potentially could be scaled in power to propel orbit transfer vehicles and future planetary probes. Thus, the Jet Propulsion Laboratory (JPL), the UM, and TsNIIMASH (a Russia Hall thruster developing institute) are teaming up to develop a high-power Hall (5 kW) thruster which can be used for planetary probe propulsion.

The Closed-Drift Hall Thruster

There are two types of Hall thrusters that have been studied at great lengths, the end-Hall thruster and the closed-drift thruster (CDT). Both engines, in principle, are capable of producing specific impulses in excess of 1500 seconds with xenon at a thrust efficiency of ~50%. However, it is the CDT, which has been developed and used in the former Soviet Union over the past twenty years, that is of the most interest to the Western space technology community.

The CDT is a coaxial device in which a magnetic field that is produced by an electromagnet is channeled between an inner ferromagnetic core (pole piece) and outer ferromagnetic ring. This configuration results in an essentially radial magnetic field with a peak strength of a few hundred gauss. This field strength is such that only the electrons are magnetized. In addition, an axial electric field is provided by applying a voltage between the anode and the downstream cathode. As the electrons stream upstream from the cathode to the anode, the $\underline{E}\times\underline{B}$ action on the electrons cause them to drift in the azimuthal direction, forming a Hall current. Through collisions, these electrons ionize propellant molecules that are injected through the anode and which are subsequently accelerated by the axial electric field. The mixture of electrons and ions in the acceleration zone means that the plasma is electrically neutral, and as such, is not space charge limited in ion current (thrust) density throughput. Since the magnetic field suppresses the axial mobility of the electrons while exerting essentially no effect on the ion dynamics, the plasma can support an axial electric

field with a potential difference close to the applied voltage between the electrodes. Thus, the bulk of the ions are accelerated to kinetic energies to within 80% of the applied discharge voltage. This combination of processes accounts for the CDT's high thrust efficiency.

Russian CDT's come in two variants; the stationary plasma thruster (SPT) (also known as the magnet layer thruster) and the anode layer thruster (TAL). The main difference between these two devices is that the SPT uses a dielectric coating to electrically insulate its acceleration channel while the TAL uses a much shallower channel enclosed within metal walls. Performance characteristics of both engines are virtually identical (~1600 sec at 50% efficiency). Although they vary in size and input power (e.g., 3.5 cm in diameter at 300 W and 20 cm in diameter at 6 kW), CDT's that are currently being considered for satellite North-South station-keeping roles typically operate at discharge voltages of 300 V, thruster currents of 4.5 A, and xenon mass flow rates of 5 mg/s. As the discussion below will show, the power level (and therefore the current and mass flow rates) which will be needed in the near future will be considerably higher.

Need for a High-Performance Vacuum Facility for Electric Propulsion Research

Although CDT's have performance characteristics that make them attractive for earth orbiting missions, the complex nature of their operation is a source of concern from a spacecraft integration point of view. For example, CDT's that use dielectric channel coatings suffer from excessive insulator erosion. Much of this erosion is due to sputtering from energetic ions near the exit of the discharge chamber [20]. TAL's, which erode metal from its channel walls, may pose an even more serious threat to spacecraft health (e.g., to the solar arrays). Such erosion poses a potential hazard to spacecraft operation since ablated insulated material could coat vital spacecraft surfaces like solar arrays and communications antennae.

In addition, there is further concern that the spacecraft could be damaged by side or back-scattered exhaust ions. The ions accelerated by the thruster travel at kinetic energies in excess of 200 eV [21]. Since a significant fraction of the exhausted particles travel at angles in excess of 45° from the thruster axis, plume divergence not only detracts from engine performance due to cosine losses from thruster canting, but also results in damage to the spacecraft due to sputtering.

The erosion/deposition characteristics in the plume of CDT's are quite complex. Experiments have shown that in the central region (45°) of the plume, the energetic ions tend to remove deposited materials from structures in such a way that the net erosion rate overwhelms the surface deposition rate of thruster effluent material [22]. At higher angles with respect to the thruster axis of symmetry, however, the opposite is true: That is, the plume tends to remove material from objects placed near its axis of symmetry, and deposits matter on objects at higher angles. The exact location where this transition occurs (and what parameters it may depend on) remains unknown.

Furthermore, the exhaust of a highly ionized plasma from a spacecraft in earth orbit may affect the electrodynamics of the spacecraft and its communication systems. Russian researchers have claimed that the operation of the engine yields "subtle changes" of the spacecraft's potential with respect to the ambient plasma [16]. This phenomenon may affect the electronics of the satellite by causing excessive spacecraft charging or coupling of plasma noise into the spacecraft structure [23].

There is also concern that the highly ionized plume might interfere with the transmission of radio waves. The impact of thruster plasma plumes on electromagnetic signals in the near-field of onboard antennas and receiving systems is of concern to spacecraft designers. Air Force spacecraft radio frequency (RF) systems can include: communications, radar, and navigation (Global Positioning System). The spacecraft designer must know whether these RF systems will be degraded and whether the impact of compensating for the degradation outweigh electric propulsion's inherent advantages. Typical radio wave-plasma interactions of concern include: reflection or refraction of a transmitted/received signal, attenuation and phase shift (scintillation), and generated noise on both signal amplitude and phase. Possible system impacts include: signal-to-noise degradation (amplitude degradation, phase noise), degradation of antenna main beam and side

lobe, and reduced cross polarization isolation (linearly polarized systems only). This could result in increased bit-error-rates (BER) for communication systems, degraded radar images/signatures for radar systems, and increased range and location errors for radio frequency navigation systems [24].

Our own research at the UM has shown that the SPT-100 has an impact on Ku-band transmissions [25]. A 17 GHz microwave illuminated through the plume of the SPT exhibited an increase in noise power floor by as much as 20 dBm and the onset of coherent signal peeks at 26 kHz harmonics [25].

The Ideal Vacuum Facility for Electric Propulsion Performance and Integration Studies

Vacuum chambers affect EP devices in a number of profound and subtle ways. Improper matching of an engine and test goals with a facility can render a series of experiments meaningless. For example, if the chamber is too small, its boundaries (walls) can affect measurements by altering the flowfield or by introducing contaminants due to tank wall erosion. If the tank pressure is too high, the background gas can artificially modify the exhaust plume as well as alter the operation of EP device itself. Thruster operation may be influenced by entrainment and/or ingestion of the background chamber molecules. This effect artificially increases the propellant mass flow rate of the engine, resulting in performance and operation changes consistent with the increased number of propellant particles. Furthermore, plume diagnostic experiments can be affected. A large partial pressure of background gas molecules can affect ion current density and energy distribution measurements by artificially increasing the local charge density through charge exchange collisions. For example, at large angles from the SPT axis, the ion energy distribution profile is dominated by low-energy charge exchange ions, the source of which is thought to be background gas, although neutral particles emanating from the cathode and thruster discharge chamber could be responsible as well [20,26]. These energy data are needed to estimate how damaging the SPT plume may be to solar arrays, for example. In order to avoid such ambiguities in interpreting data, certain chamber pressure criteria should be strictly adhered to.

Randolph et al. [27] suggest that in order to characterize a 1 kW Hall thruster in terms of performance, electromagnetic interference (EMI), intermediate-field (<1.2 m) plume properties, and life, the chamber pressure should be no more than 5×10^{-5} Torr, 5×10^{-5} Torr, 1.3×10^{-5} Torr, and 5×10^{-6} Torr, respectively. The pressure at low earth orbit and at Geosynchronous orbit are approximately 10^{-6} Torr and 10^{-10} Torr, respectively, so a perfect simulation of pressure is not necessary. Further, Randolph also shows that tank design, in addition to tank pressure, plays a role in thruster life tests since the amount of sputtered tank wall material which deposits on thruster surfaces depends on the geometry and size of the vacuum chamber.

Arcjets operate at much higher pressures and propellant flow rates than Hall thrusters and as such, are probably less susceptible to facility affects in terms of performance and operation. Given the fact that the exit pressure of a 1 kW arcjet is of the order of one Torr compared to the exit pressure of 10^{-3} Torr for the Hall thruster, the pressure restriction for making performance measurements with the arcjet is probably three orders of magnitude less severe (i.e., 5×10^{-2} Torr for the arcjet vs. 5×10^{-5} Torr for the Hall thruster). Studies at NASA LeRC confirm this supposition. Requirements for plume and EMI studies would almost certainly remain unchanged and the effect of chamber pressure on thruster life is not clearly understood for all EP devices.

In terms of chamber size, one could argue that since the characteristic length of a typical satellite is between 1 and 10 m, the chamber should be of this size as well (i.e., at 5 m in diameter) in order to make realistic plume measurements at a location from the exit plane which is representative of the distance actual flight hardware components are likely to be placed with respect to EP thrusters. Furthermore, the chamber should be as close to a sphere as possible with the thruster operating in the center so that a complete study of the plume can be made in all directions (i.e., 8π radians in spherical coordinates) and to maximize the path length that sputtered wall material must travel to the thruster. Both of these assertions are corroborated by Randolph's analysis which suggests that a cylindrical chamber with a length-to-diameter ratio (L/D) of 1.2

(i.e., close to spherical) with a characteristic length of several meters is optimum [27]. As stated above, the chamber should have adequate pumping to maintain the chamber pressures mentioned above: This is critical. For an arcjet, this means large oil diffusion pumps are necessary since cryopumping systems are not effective with H_2 or N_2, while for electrostatic thrusters that use xenon, cryopumped facilities are best to avoid thruster contamination with diffusion pump oil.

Even though one or two university vacuum facilities in the nation, at most, can adhere to even the most lenient of the aforementioned criteria for adequate chamber pressure for 1 kW-class EP thrusters, no university installation even approaches the pumping speed needed for the higher-powered devices which are anticipated for the near-future. The next section will present an argument on why high-power EP systems are forthcoming: Universities must be ready to support such engine research.

High-Power Electric Propulsion

Communication satellites are becoming both smaller and larger. This fact is acknowledged throughout the EP community. Hughes Corporation's recent announcement of the HS-702 satellite with up to 15 kW of solar array power (first launch in 1998), more than twice the power available from the largest current communication satellite, suggests that EP systems will also have to double (or triple) in power from the current 2 kW to 4 or 6 kW systems. This means that vacuum systems will have to be modified to handle the added propellant flow rates demanded by these higher power thrusters. NASA LeRC and JPL have recently upgraded their pumping systems in anticipation of the higher powered thrusters. NASA LeRC has recently initiated another plan to further add pumping speed to its largest facility. Moreover, the fact that an emphasis of the DURIP is for enhancing the capacity of the nation's EP test facilities implies that the Air Force recognizes the role universities play in EP research. Universities train students who will eventually work on EP at government laboratories and in industry. Universities, by their very nature, are allowed to take more risk and to do basic research which may not be appropriate in government and industrial settings. Thus, the university not only serves a vital link in the pipeline for researchers and engineers, but for ideas.

DURIP Summary

DURIP funds were solicited and used to pay for the following modifications to the EP experimental facilities at the UM:

1) A state-of-the-art xenon cryopumping system to increase the chamber pumping speed by a factor of five (and thus decrease the facility pressure by this factor); and

2) A dye/pump laser system to perform laser-induced fluorescence (LIF) measurements in EP thruster plumes.

The expected outcome of these modifications is to make the UM EP vacuum facility a world-class national resource that the DOD, NASA, and other universities can use for EP research. As the following section shows, the facility prior to the above modifications was matched at any no other university and few government laboratories. The relatively modest funds solicited from DURIP will bring the UM facility to the next level of excellence that rivals the largest that government laboratories have to offer. This is made possible by our approach of using advance cryopumping and laser technology which in the end offer the most cost-effective performance.

University of Michigan Laboratory Hardware Prior to DURIP

The centerpiece of the Plasmadynamics and Electric Propulsion Laboratory (PEPL) at the University of Michigan is a large vacuum chamber that was built in the early 1960's by the Bendix corporation and was later donated to the university in 1982 (cf. Fig. 1). This cylindrical stainless-steel clad tank, which is 9 m long and 6 m in diameter (L/D=1.5), is the largest vacuum facility of its kind at any university in the

nation. The facility is supported by six 81-cm-diameter, 32,000 l/s diffusion pumps (with water-cooled coldtraps) backed by two 2,000 cfm blowers and four 400 cfm mechanical pumps. These pumps give the facility an overall pumping speed of over 180,000 l/s on nitrogen at 10^{-4} Torr and 27,000 l/s on xenon at 10^{-5} Torr. In addition, a Polycold PFC-1100 closed-loop refrigeration system (water cryopump) has been installed above two of the diffusion pumps to serve as a water cryopump.

With the current pumping system, the background chamber pressure is maintained to less than 3×10^{-4} Torr during the operation of a 1 kW arcjet on 16 mg/s of hydrogen or 47 mg/s of simulated hydrazine, and 4×10^{-5} Torr during the operation of a 1.35 kW SPT-100 on 5 mg/s of xenon. Thus, the current pumping system is barely adequate to characterize the intermediate-field plume of an SPT-100 and, strictly speaking, is not high enough to study EMI or thruster erosion processes [27].

PEPL operates several engines (cf. Fig. 2) including a 1 kW arcjet from NASA LeRC, a 1 kW end-Hall thruster from NASA LeRC, a 1.35 kW SPT from the Moscow Aviation Institute (MAI), a flight-qualified 1.35 kW SPT-100 from FAKEL Enterprises (Russia) and SS/L, a 300 kW pulsed MPD thruster, and a 1.35 kW D-55 TAL from TsNIIMASH (Russia). An exclusive agreement is being initiated which allows PEPL to operate a 5-kW-class D-55 TAL[1].

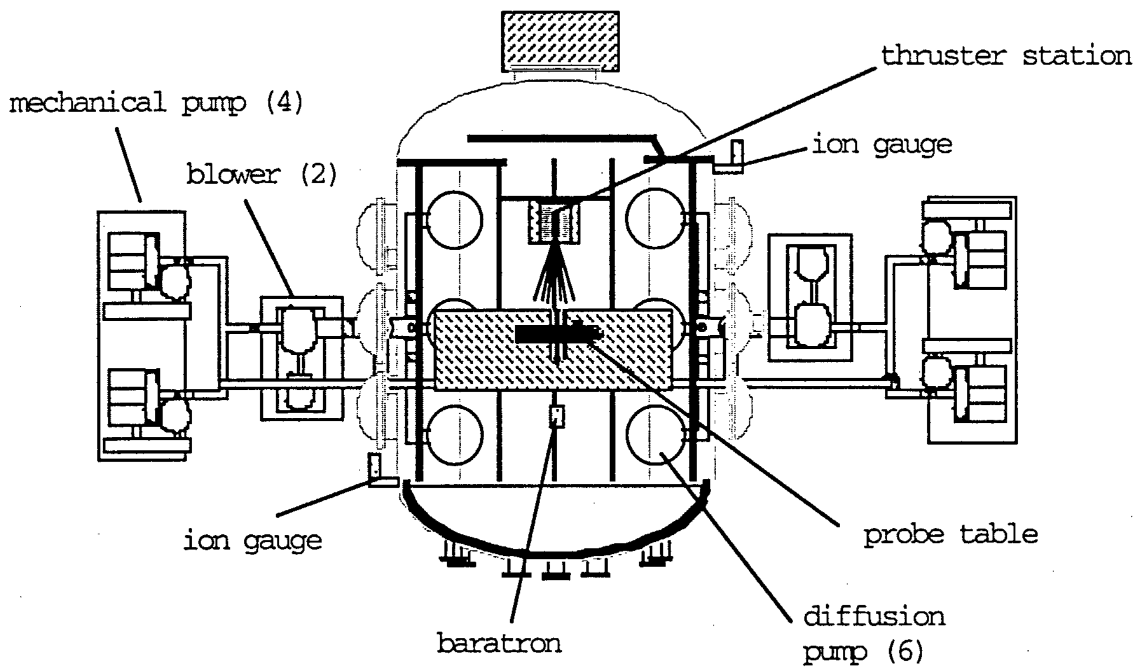


Figure 1: The main vacuum chamber of the laboratory. This 9-m-long by 6-m-diameter chamber is supported by an array of pumps, giving it a xenon pumping speed of 27,000 l/s at 10 microtorr.

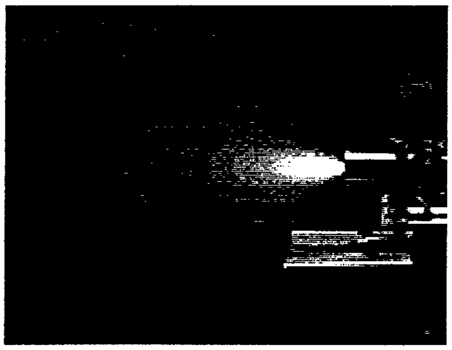
Data Acquisition and Thruster Support Equipment

Figure 3 gives an overall view of the PEPL test complex, showing the two chambers, the computer stations, and the diagnostics support equipment.

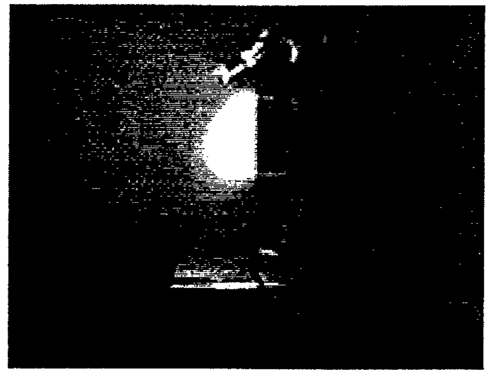
[1] Experiments with this high-power thruster will commence in the Winter of 1996 even though it is not clear if the current pumping system can provide a low enough pressure to make plume measurements.

Data acquisition (DAQ) at PEPL is accomplished via a Macintosh based DAQ system developed by National Instruments (LabView). The system includes four SCXI-1120 8-channel isolation amplifiers which are used in conjunction with an NB-MIO-16XH-18 data acquisition board to provide thirty-two isolated differential input channels that are sampled at a maximum rate of 55 kSamples/sec. The entire system, which monitors thruster, diagnostics, and tank operations, is controlled by LABVIEW 2 software.

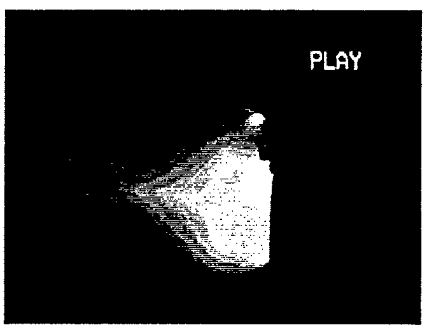
a) 1 kW Arcjet (NASA LeRC)



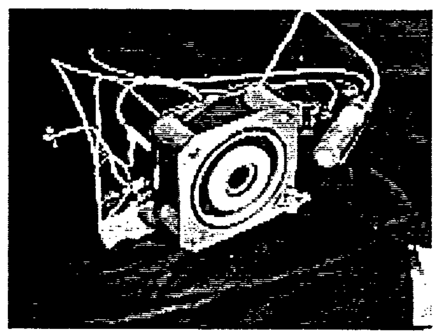
b) 1 kW end-Hall Thruster (NASA LeRC)



c) 1.35 kW SPT (MAI)



d) 1.35 kW SPT (MAI)



e) SPT-100 (FAKEL)

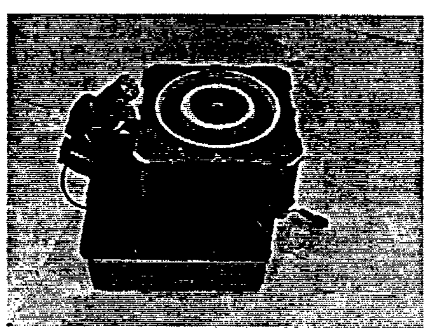


Figure 2: Captured video images of PEPL electric propulsion devices [nominal propellants]: a) 1 kW arcjet [hydrogen/simulated hydrazine/simulated ammonia], b) 1 kW end-Hall thruster [argon], c) & d) 1.35 kW stationary plasma thruster (SPT) [krypton/xenon], and e) flight-qualified 1.35 kW SPT-100 [xenon].

PEPL has a five node Ethernet zone (four computers and a printer) with direct access to the UM network. PEPL currently has an additional six IP addresses assigned to it for use by contract sponsors and users of the facility (e.g., to transfer data to a sponsor's host computer via a sponsor-owned computer).

Propellant is supplied to the thruster from compressed gas bottles through stainless-steel feed lines. The hydrogen bottles are stored in a shed outside of the laboratory for safety reasons. Hydrogen leak detectors are used to track hydrogen leaks through the propellant feed and vacuum exhaust systems. Additionally, nitrogen is injected into each of the mechanical pump's gas ballasts and exhaust manifolds to dilute the hydrogen prior to atmospheric exhaust and to prevent its accumulation in the exhaust plumbing.

Propellant flow is controlled and monitored with an array of MKS 1159B mass flow controllers specially calibrated for light and heavy gases with an accuracy of 1%. The flow controllers are periodically calibrated with a calibration rig that measures gas pressure and temperature changes with time in an evacuated chamber of known volume to estimate the mass flow rate (via the ideal gas law).

Thruster operation is visually monitored and stored with a Sony camcorder connected to a JVC Super VHS Cassette Recorder. A filter wheel is placed in front of the video camera to allow band-pass filtered images of the plume to be stored on film. Video frames are downloaded to and stored on a Macintosh computer for image processing and analysis through the use of a frame grabbing system developed by Radius (cf. Fig. 2).

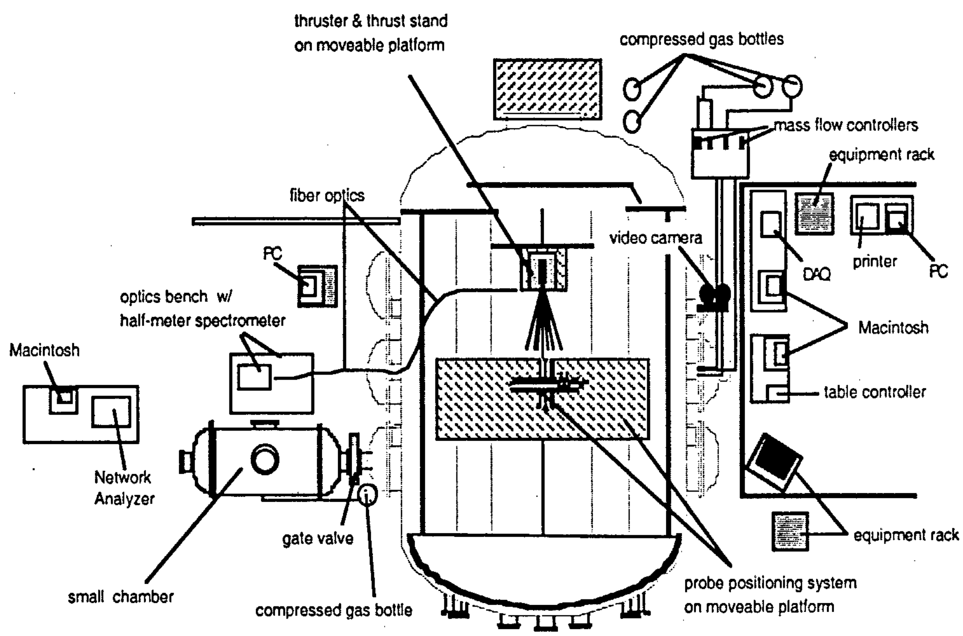


Figure 3: Overview of PEPL test facility and diagnostics.

Thruster Plume and Performance Diagnostics Prior to DURIP

Probe diagnostics used at PEPL include: Langmuir probes for electron density, temperature, and plasma potential (electric field); Hall probes for the magnetic field; impact pressure probes for stagnation and static pressure; ion energy analyzers for ion energy distribution; Faraday cups and "button probes" for ion current density; emissive probes for the electric field, and heat flux sensors.

Probe measurements, both in the near and far-fields, are performed through the use of a custom-made probe positioning system developed by New England Affiliated Technologies (NEAT). The probe positioning table has two degrees of freedom as well as angular freedom in the horizontal plane (i.e., radial, axial, and θ). The table contains two rotary platforms on a 1.8-m-long linear stage in the radial direction that is mounted on a 0.9-m-travel axial stage. The rotary actuators not only allow probes to be rotated to minimize measurement errors due to probe misalignment with the flow, but also for the purpose of characterizing the local flow field. The system allows for sweeps with two independently controlled probe rakes at a time at radial speeds in excess of 60 cm/s with an absolute position accuracy of 0.15 mm. The system is operated by its own Macintosh-driven control station via LABVIEW II software. Like the thruster station, the entire probe positioning system is mounted on a movable platform to allow for measurements to be made throughout the chamber .

Transient measurements (e.g., plume property fluctuations) are monitored with a four channel Tektronix TDS540 digital oscilloscope capable of collecting 250 million Samples/sec at a bandwidth of 500 MHz. Each channel can handle 50,000 pts and in single channel mode, the unit can collect samples at a rate of 1 GSamples/sec. The oscilloscope also contains signal processing firmware and can be controlled by a Macintosh computer via a National Instruments NB-MIO-GPIB board.

All thruster performance measurements are made with an inverted pendulum type thrust stand based on the NASA LeRC design, the industry standard. The thruster is mounted to an aluminum plate that is connected to the core of a Lucas Schaevitz model 100-HR Linear Variable Differential Transformer (LVDT). The core resides within a LVDT coil that is mounted to the base of the thrust stand. Thus, the thrust stand measures the displacement of the aluminum plate due to engine thrust. The output from the LVDT is routed to a Lucas Schaevitz DTR-451 Digital Transducer Readout (DTR) and to the data acquisition system. Thruster/thrust-stand leveling is performed manually prior to chamber pump-down so that the LVDT core is in its null position within the coil. A remotely-controlled stepper motor driven pulley system is employed to provide in-situ thrust stand calibration by loading and off-loading small weights to simulate thrust. A linear curve-fit of LVDT displacement vs. thrust is then obtained and used for performance measurements. Soon after the thruster is turned off, a post-test calibration is performed. The springs of the stand are made with extra stiffness to minimize thruster deflection, thus allowing plume measurements to be made concurrently with performance measurements. The entire thrust stand assembly is housed within a water-cooled stainless steel shroud. Thrust data, based on the predetermined curve fit, are displayed and simultaneously stored on the hard disk by the DAQ system. The DAQ system also reads mass flow rate, current, and voltage, enabling it to calculate thrust efficiency and specific impulse in real-time.

Spectroscopic plume measurements are made with a Spex Industries model 500M Czerny-Turner type spectrometer. The spectrometer has a focal length of 0.5 meters, an f/4 aperture, and a dual exit assembly to allow for the installation of both a Photo Diode Array and a Photo Multiplier Tube (PMT). A 1800 gr/mm holographic grating, blazed at 500 nm, is currently used for all measurements, giving the spectrometer a dispersion of 1.2 nm/mm, a spectral range between 120-1000 nm, and a wavelength resolution of 0.015 nm. Light detection is achieved using a Hamamatsu R928 PMT powered by a Spex-35870-1 high voltage power supply. PMT voltage is computer controlled via the Spex Datascan unit. Spectrometer scans are monitored, controlled, and stored on a Gateway 2000 486 personal computer (PC) through Spex Industries' Autoscan software. A Stanford Research SR850 Dual Phase Analog Lock-in Amplifier is sometimes used, in conjunction with a chopper, to provide phase-locked spectrometer scans for "noisy" spectra.

Because of the large size of the chamber, direct optical access to the exit of the thruster is difficult to achieve. Thus, light from the thruster plume is focused onto the face of a 100-micron-diameter silica optical fiber by a 25-mm-diameter achromatic lens within the chamber, and is transmitted to the spectrometer via a vacuum feedthrough. The exiting light from the optical fiber is then focused onto the entrance slit of the spectrometer by a second achromatic lens.

Characterization of the spectral response for this imaging system was made using a tungsten lamp as a light source in place of the thruster plume. Emissivity values for tungsten were used to determine the actual spectral output of the lamp. True lamp intensity along with corresponding measured intensity acquired from the spectrometer PMT signal was then used to determine the system's spectral response. The spectral response function was used to correct the measured intensity at a given wavelength to its true value.

In order to allow radial scans to be made at or near the thruster exit plane, the collection optics in the large chamber are mounted on a PC-controlled NEAT 20 cm linear positioning table that is vertically mounted to the side of the thruster station. This allows the collection optics to be position approximately 10 cm above or below the center of the plume. When not in use, the collection lens is stored in a "safe-box" at the top of the stage to protect it from the plume.

PEPL also operates one of the most advanced microwave interferometers[2] in existence to measure electron number density. This interferometer is composed of two horns which are attached vertically on a projecting boom that is mounted on the probe table and is swept through the plume (cf. Fig. 4). In-situ electron number density measurements are made by recording the phase change of the microwave signal (17.5 GHz) as it passes through the plasma. A network analyzer (Hewlett Packard 8753D), which was purchased through an AFOSR grant, performs the interferometeric measurements by serving as a stable microwave source and a highly sensitive receiver. This network analyzer is controlled by a Macintosh computer via LabView through a GPIB interface card.

Due to the long distance between the network analyzer outside the chamber and the antenna system inside the chamber, a frequency up-down converter is utilized in order to transmit a lower frequency over that distance with corresponding lower losses and lower phase inaccuracies. The up-down converter, placed near to the antennas, shifts the 2.5 GHz signal from the network analyzer to 17.5 GHz by using a 15 GHz local oscillator.

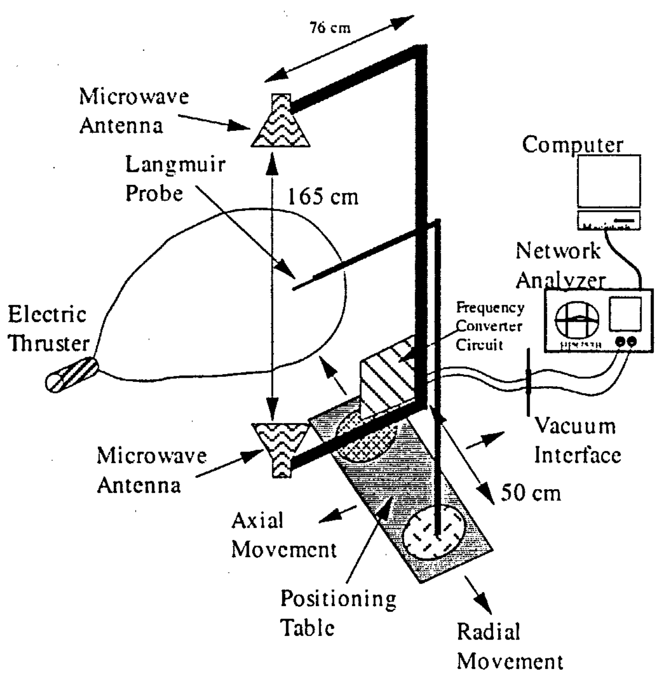


Figure 4: Sketch of the 17.5 GHz interferometer, Langmuir probe, and electric thruster. Included in the microwave system are two lens corrected horn antennas, a frequency converter circuit (2.5 GHz to 17.5 GHz), network analyzer, and computer controller.

[2]Developed with Prof. Brian E. Gilchrist of the EECS Department at the University of Michigan, in part with AFOSR funding.

This system is capable of generating 2-dimensional (axial and radial) electron density profiles throughout the plume of a thruster by moving the system in the axial and radial directions via the positioning system, and through use of the Abel inversion technique to convert integrated signals into local plume properties. Since the system is designed to work throughout the Ku band (12-18 GHz), it can also be used to study how Ku band communications and radar signals are affected by the thruster plume. For example, a spectrum analyzer (Hewlett-Packard 8563E) is used in conjunction with this system to characterize the manner in which Ku band signals are modified by the thruster plume [25]. Other bands will be studied as part of an AFOSR grant by simply replacing the horns and modifying the microwave generation circuitry.

Equipment Purchased from DURIP Funds

DURIP funds were used to purchase a xenon cryopumping system and an LIF system to enhance greatly PEPL's capability to perform EP spacecraft integration and development research. Each of the purchased systems are described below.

Cryopumping System

Table I showing the various tank pressures which are required for certain EP research activities is presented below for the sake of convenience. In general, chamber pressures of 10^{-5} Torr or less are desirable for spacecraft integration work. In order to achieve this pressure, large pumping speeds are necessary. For example, in order to maintain a pressure of 10^{-5} Torr with an SPT-100 (5 mg/s of xenon), the vacuum facility would have to have a xenon pumping speed of over 70,000 l/s. Thus, in order to operate a 5-kW-class Hall thruster at this same pressure, a pumping speed of over 100,000 l/s is necessary.

There are several means of achieving this level of pumping speed. A large gaseous He refrigeration system with LN_2 cryopanels - the kind currently used at NASA LeRC - is prohibitively expensive for any university. The system in Tank-5 at NASA LeRC has a xenon pumping speed of 150,000 l/s [19], but at a cost of over $4M. Another approach is to use a bank of diffusion pumps or cryotubs. Oil diffusion pumps are somewhat ineffective on xenon and pose the danger of thruster contamination due to oil backstreaming. As an example, Tank 5 has twenty 0.8-m-diameter diffusion pumps for a combined pumping speed of only 90,000 l/s [19]. This figure is consistent with PEPL's pumping estimate of 27,000 l/s with six similar pumps. Thus, over forty 0.8-m-diameter diffusion pumps would be required to reach 100,000+ l/s on xenon. Further, if one minimizes backstreaming with cryo-baffles and cold-traps, pumping speed suffers greatly. To achieve a pumping speed of over 100,000 l/s on xenon with conventional cryotubs, several 1.2-m-diameter units would be necessary, at a cost of at least $80,000 each when required facility modifications are taken into account. Moreover, consumables (LN_2 and/or diffusion pump oil) are required for all of the pumping scenarios above, the cost of which, particularly the LN_2, can reach several hundred dollars a day.

Table I: Required chamber pressure as a function of research activity for the Hall thruster and arcjet from the analysis of Reference [27].

Activity	Hall Thruster	Arcjet
Performance	5.0E-05 Torr	5.0E-02 Torr
EMI	5.0E-05 Torr	5.0E-05 Torr
Intermediate Plume	1.3E-05 Torr	1.3E-05 Torr
Life	5.0E-06 Torr	unknown

Therefore, a cryopumping system is needed which requires little or no consumables, and provides high performance in a cost effective manner. In addition, such a system should be robust and modular, so that

segments of the system can be removed for repair or refurbishment without taking the entire system off-line. The system that had been identified which would satisfy these requirements is a bank of gaseous He cold-heads. However, the technological maturity of such a system was not sufficient at the time, and the cost was much higher than anticipated. It should be noted that such a system could be used to augment the xenon cryopumping system that was actually purchased.

The system that was purchased consists of four CVI TM-1200 nude (reentry) cryopumps. These are the same pumps used for CVI's 1.2 m cryotub, however the sail is enclosed within a box with three louvered sides. The entire box is placed within the vacuum chamber. Because of the low conductance losses associated with this configuration in comparison to conventional tubs, each pump has twice the pumping speed of its conventional counterpart (35,000 l/s vs. 15,000 l/s on xenon). A number of benchmark tests were performed to measure the pumping speed of the facility. The activities done to install these pumps include:

Remove the existing LN_2 shrouds which served to purpose but reduced the interior volume of the chamber and may have introduced leaks;

- Clean the entire surface of the chamber (mostly diffusion pumps oil);
- Drain and cap the diffusion pumps;
- Purchase and install a 6,000 gallon LN_2 tank to support the TM-1200 pumps
- Install cryopumps;
- Repair leaks, reducing the leak rate by two orders of magnitude (400 sccm to 4 sccm); and
- Purchase new pressure monitoring devices.

Garner Facility Services, Inc. was hired out of University of Michigan cost-sharing funds to be the general contractor of the work. The xenon pumping speed was measured at approximately 140,000 l/s and the nitrogen pumping speed at 280,000 l/s. The base pressure of the facility is 3×10^{-7} Torr, two orders of magnitude lower than before. The facility has been fully operational since May and has worked flawlessly with a number of commercial and laboratory Hall and ion thrusters. A suite of papers presented at the last major conference in the electric propulsion field (last summer in Cleveland, OH) utilized the new facility. A sketch of the modified facility is shown in Fig. 5.

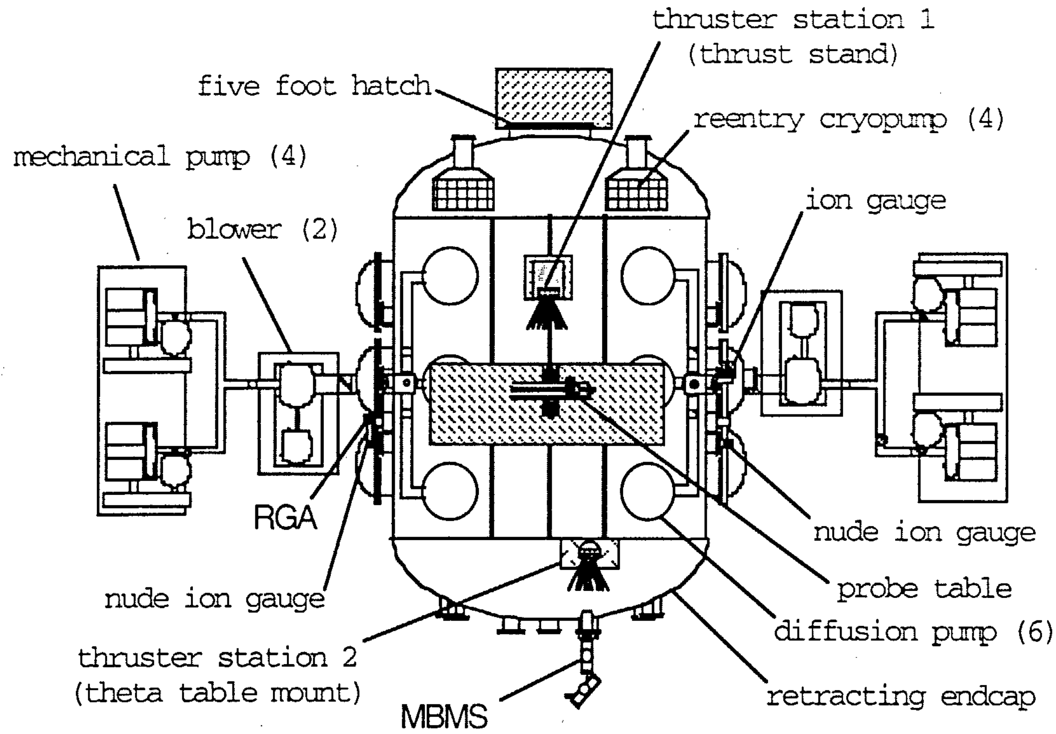


Figure 5: Sketch of 140,000 l/s xenon pumping system purchased from DURIP funds. The system is comprised of four CVI TM-1200 nude (reentry) cryopumps each with a measured xenon pumping speed of 35,000 l/s.

LIF System

Laser-Induced Fluorescence (LIF) has become a staple in the diagnostics suite of electric propulsion research [28-31]. The basic principle behind LIF is quite simple. Coherent laser light that is tuned to a wavelength of a particular transition of interest illuminates a selected volume of the plume. The tuned laser light excites a molecule, initiating an electronic transition to an upper state. Some of these molecules radiatively decay and emit radiation at or near the wavelength of the incident laser light. This radiation is then collected and analyzed to determine certain attributes of the plume gas. For example, LIF can be used to measure heavy particle translational temperature by looking at the Doppler broadening of a line (transition). Since translational is nothing more than a reference to the random velocity distribution of constituents, Doppler broadening - a measure of the integrated Doppler "shifts" due to random particle motion - is as direct a means of measuring this quantity as is possible. Further, by adjusting the optics appropriately, LIF can be used to measure the bulk velocity of the plume by measuring the total Doppler shift of the laser in a particular direction [29, 31]. LIF can also be used to measure electron number density through stark broadening, species concentrations, and the distribution of energy states for a particular substance [30].

Although LIF has been applied to EP diagnostics with great success, the vast majority of these measurements have taken place at background pressures which almost certainly impact the thruster operation, and therefore, the fidelity of the measurements. For example, LIF measurements with arcjets to date have taken place in chambers with pressures between 55 mtorr and over 1 Torr [28-30]. As attractive as it is to characterize flowfield with non-intrusive means, it is imperative that these measurements take place at pressures which will not affect the flow. For example, the pressure in one study was so high that the evidence of shocks existing in the plume was seen. For this case, the flow was observed to decelerate after

a certain distance from the thruster plane, an obvious artifact due to the existence of shocks. Thus, with the exception of NASA LeRC and possibly the Aerospace Corporation, no other EP experimental facility in the nation of adequate pumping speed is equipped to perform LIF measurements on Hall thrusters.

DURIP funds were used to purchase two lasers - a pump laser and a ring dye laser - which comprise the bulk of a new laser diagnostics facility at PEPL. The Coherent model 899-29 Autoscan II ring dye laser is capable of outputting light within a spectral range of 375 nm - 900 nm (with appropriate dyes) with a linewidth of less than 500 kHz rms. The single frequency ring laser is computer controlled and has a wavelength meter attached to it which measures the laser frequency within ±200 MHz (0.0067 cm^{-1}). If future applications should dictate, the laser is capable of incorporating a frequency doubler as well as a Dye-to-Ti:Sapphire conversion kit at modest cost. The dye laser will be pumped by a Coherent Innova 400-15 argon ion laser. The pump laser produces 15 W of power on all measurement spectral lines. This pump laser should enable the dye laser to generate several hundred milliwatts of power over the spectral range of interest.

Major Purchase Items from DURIP Fund

4	CVI TM-1200 Nude Cryopumps (each 35,000 l/s xenon, 75,000 l/s nitrogen)
1	6000 gallon liquid nitrogen tank from BOC gases
	Garner Facility Services, Inc. was hired as general contractor to install pumping system
1	Coherent Innova Sabre R 20/4 DBW Ion Laser System
1	Coherent Model 899-29 Actively Stabilized Scanning Single-frequency Ring Dye Laser
2	Dye circulator (one for the Red Dye and one for the UV dye
1	TMC 10' optics table
	Assorted equipment for laser system and construction of laser enclosure.

Total Funds from DURIP:	$415,000
Total Funds from Michigan:	$111.000
Total Funds for Project:	$526,000

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